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BEHAVIOR OF CARBON FIBER REINFORCED POLYMER STRENGTHENED REACTIVE POWDER CONCRETE COLUMNS

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ABSTRACT

An experimental investigation was conducted to investigate the behavior of ultra-high strength reactive concrete (RPC) columns before and after strengthening with carbon fiber reinforced polymer (CFRP) sheets jacketing under eccentric axial load. Twelve columns were tested up to failure, strengthened and retested to examine strengthening efficiency and to evaluate the effects of variation of the concrete type (normal or RPC), presence of steel fibers and main steel reinforcement ratio. Experimental results showed that CFRP jacketing increases the ultimate failure load of strengthened columns up to 185%, highly stiffens them (reduces lateral displacements) and allow more ductile failure than the original columns. Also, inclusion of steel fibers in RPC columns increases failure loads up to 86%, prevents palling of the concrete cover and increase the ductility.

Key words: Reactive Powder Concrete, Columns, Carbon Fiber Reinforced Polymer, Strengthening.

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1. INTRODUCTION

Reactive powder concrete (RPC) is an ultra high strength, low porosity cement-based composite with high ductility. Unlike conventional concrete, RPC containing a significant amount of steel fibers exhibits high ductility and toughness (energy absorption) characteristics [1, 2]. In addition to its ultra-strength characteristic, RPC

has other high performance properties, such as low permeability, limited shrinkage, increased corrosion and abrasion resistance and increased durability. RPC is composed of particles with similar elastic moduli and is graded for dense compaction, thereby, reducing the differential tensile strain and increasing enormously the ultimate load carrying capacity of the material l [3, 4, 5].

Fiber reinforced polymers (FRPs) are high performance materials that consist of high strength fibers embedded in a polymer matrix to combine the strength of the fibers with the stability of the polymer resins [6, 7]. FRPs have unique properties making them extremely attractive for structural applications. They offer better strengthening alternative to traditional steel jacketing because they are durable, noncorrosive, have high strength-to-weight and stiffness-to-weight ratios, possess good fatigue behavior and allow easy handling and installation [6, 8–10].

Strengthening concrete columns with FRP jackets has proved to be very effective in enhancing ductility and axial load capacity [6, 8, 11, 12]. FRP confinement increases the lateral pressure on the column which prevents concrete expansion and cause the development of a triaxial stress field within the confined column. The axial strength and ductility of the confined concrete increases with the increased lateral pressure which result in an increase in the concrete's compressive strength and an increase in the strain at which the concrete crushes [8, 10, 11].

The confinement effectiveness of FRP jackets depends on different parameters, namely, the type of concrete, steel reinforcement, thickness of FRP jackets (number of layers) and stiffness and loading conditions [7, 8, 10]. FRP confinement is more effective for circular columns than for square or rectangular columns. This is because the lateral expansion of concrete under compression is uniformly confined in a circular column, unlike in rectangular one where confinement is concentrated at the corners rather than over the entire perimeter [8, 9, 11, 13].

2. FRP STRENGTHENING OF ECCENTRICALLY LOADED COLUMNS

Columns can be strengthened to increase the axial, shear and flexural capacities for a variety of reasons such as eccentric loading, lack of confinement, seismic loading, accidental impacts and corrosion [8]. In field applications, most columns are not under perfect concentric loading. This produces a non-uniform confining stress due to the strain gradient which in turn reduces the effectiveness of column [14].

Parvin and Wang (2001) [14] found that FRP wrap was effective in strengthening of eccentrically loaded square columns, and that the eccentricity diminished the axial load capacity and corresponding axial deflection. Similar observations were also noted by Li and Hadi (2003) [15] and Hadi (2006) [16] for eccentrically loaded circular concrete columns wrapped with CFRP sheets.

Research conducted by El Maaddawy (2009) [17] and Song et al. (2013) [18] indicated that as the magnitude of eccentricity increased, the gain in strength due to FRP wrap decreased and the midheight lateral displacement of the columns increased. This was also concluded by Al-Musawi (2012) [19] for CFRP wrapped for reinforced normal and self-compacting concrete rectangular columns under eccentric loading.

Malik and Foster (2010) [6] found that CFRP confinement effectiveness decreases in concentrically loaded FRP confined RPC columns because of the lower dilation of RPC under axial load. For the eccentrically loaded columns the CFRP was shown to

be effective in controlling the failure of the columns with considerable straining occurring beyond the peak loading.

Sadeghian et al. (2010) [20] found that bending stiffness and moment capacity of large-scale rectangular concrete columns increased with the addition of longitudinal layers of FRP, but curvature capacity did not increase. For the wrap configuration with angle orientation, in addition to bending stiffness and moment capacity, the curvature capacity also improved.

Benzaid and Mesbah (2013) [11] stated that the effect of CFRP confinement on the bearing and deformation capacities of columns decreases with increasing concrete strength, thus FRP confined low strength concrete columns had higher gain in their load capacity than high strength concrete columns. Similar results were also recorded by Li and Hadi (2003) [15], Hadi (2006) [16] and Song et al. (2013) [18].

Most of the available literature dealt with “initial” strengthening of “conventional” concrete columns with FRP jackets. In contrast, the objective of the present work is to investigate the behavior of RPC columns failed under eccentric compression loads then strengthened with CFRP sheets and retested under the same conditions to examine strengthening effectiveness of damaged or deteriorated columns in existing structures.

3. EXPERIMENTAL PROGRAM

In the experimental program twelve reinforced concrete square columns were cast, tested up to failure under eccentric compression loading, strengthened after failure with CFRP jacketing and retested. Three of these columns were fabricated with normal strength concrete (NC) and nine with reactive powder concrete (RPC). Details of these main stages are given in the following.

3.1. Materials Properties

Ordinary Portland Cement (ASTM Type I) was used for both NC and RPC mixtures. Naturals and of 4.75 mm maximum size and very fine sand with maximum size of 600 µmwereusedasfine aggregate for NC and RPC, respectively. Crushed gravel with maximum size of 10 and 8 mm was used for NC and RPC, respectively.

In addition, RPC mixtures contained densified silica fume ($SiO_2 > 98\%$), modified polycarboxylates based high range water reducing admixture (super plasticizer)(density = 1.09 kg/l at 20 °C) and hooked end short steel fibers with aspect ratio of 65 (length=13 mm and diameter =0.2 mm) and yield stress of 1130 MPa.

Deformed steel bars of nominal diameter of 6 mm for closed ties and 10, 12, and 16 mm for main reinforcement were used in the tested columns. Table 1 gives the tensile test results conducted on samples of the used steel bars.

Table 1 Tensile test results of steel bars*

Nominal diameter(mm)	6	10	12	16
Yield stress (MPa)	435	482	532	528
Ultimate strength (MPa)	535	573	715	707

*Carried out at the College of Engineering, Al-Mustansiriya University

3.2. Mixes and Mixing Procedure

Based on several trial mixes, one NC mix and three RPC mixes that differ from each other only in volumetric steel fibers ratio (V_f) were adopted in this work as shown in Table 2.

Table 2 Mix Proportions of NC and RPC.

Mix	Cement kg/m^3	Sand kg/m^3	Gravel kg/m^3	Silica fume* %	Silica fume kg/m^3	w/c	Super-plasticizer* %	Steel fiber** %	Steel fiber kg/m^3
RPC0	900	990	-	25	225	0.18	5	0	0
RPC0.75	900	990	-	25	225	0.18	5	0.75	58.5
RPC1.5	900	990	-	25	225	0.18	5	1.5	117
NC	400	600	1200	0	0	0.45	0	0	0

*Percent of cement weight.**Percent of mix volume.

In the present work, mixing was performed by using 0.19 m^3 capacity horizontal rotary mixer. Firstly, the silica fume powder was mixed in dry state with the required quantity of sand for 5 minutes. Then, cement and crushed gravel were loaded into the mixer and mixed for another 5 minutes. The required amount of tap water was added to the rotary mixer within 1 minute. Then all the super plasticizers were added and mixed for an additional 5 minutes. Finally when used, steel fibers were dispersed uniformly and mixed for an additional 2 minutes.

A total of four batches of concrete (1 normal and 3 reactive powder) were used to cast the columns by using three wooden molds. Each batch was enough to cast three columns with three cubes of 100 mm size to determine the compressive strength of concrete. Concrete compaction was performed through a table vibrator. After 24 hours, specimens were demolded and cured in water at room temperature for 28 days before testing.

3.3. Details of Tested Columns

All twelve columns (3 NC and 9 RPC) were identical in nominal dimensions with square section 120 mm × 120 mm through the middle portion (500 mm) of the column total height of 1000 mm. Column ends were designed as corbels to easily apply eccentric loads. Eccentricity waskept constant at **e = 60 mm = b/2**(Figure 1).

All columns were reinforced longitudinally (vertically) with four steel bars with nominal diameter 10, 12 or 16 mm (as variable) which were placed at each corner of specimens. The columns contained the same transverse reinforcement of deformed bars with 6 mm nominal diameter spaced at 120 mm. The end corbels were reinforced with additional steel to prevent premature failure at ends during the test and to ensure failure in the middle portion. Figure 1 shows the geometry and reinforcement details of the specimens. The test program and specimen details are summarized in Table 3, where (NC) refers to Normal Concrete , (RPC) refers to Reactive Powder Concrete, the numbers 10, 12 and 16 refer to longitudinal steel bar diameter and numbers 00 , 0.75 and 1.5 refer to steel fibers content as a percentage of concrete volume

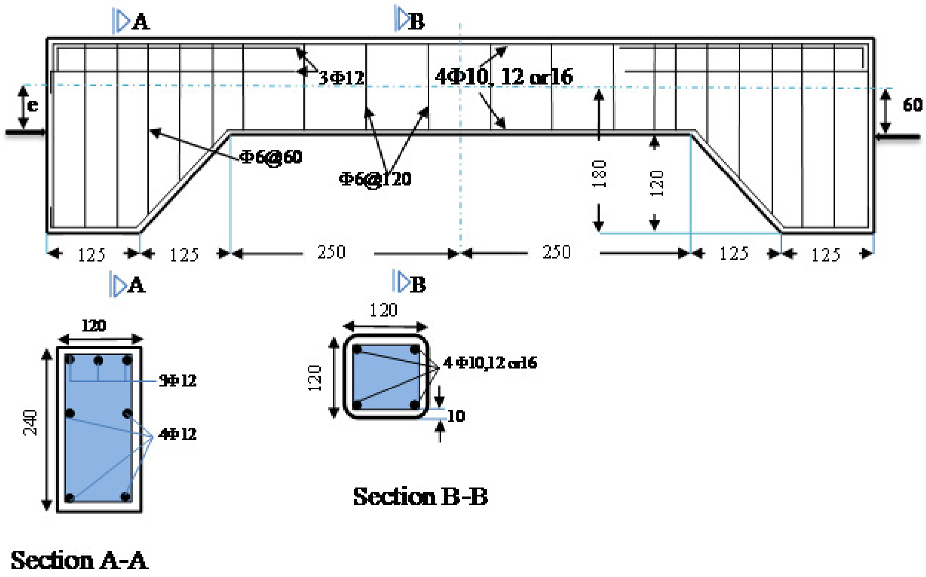

Figure 1 Details of tested specimen (All dimensions in mm).

Table 3 Details of tested columns

Column designation	Concrete type	Main longitudinal* reinforcement	Main longitudinal reinforcement ratio (ρ) %	Steel fiber (%)
NC-10-00	Normal	4Ø10	2.18	0
NC-12-00		4Ø12	3.14	
NC-16-00		4Ø16	5.58	
RPC-10-00	Reactive Powder	4Ø10	2.18	0
RPC-12-00		4Ø12	3.14	
RPC-16-00		4Ø16	5.58	
RPC-10-0.75	Reactive Powder	4Ø10	2.18	0.75
RPC-12-0.75		4Ø12	3.14	
RPC-16-0.75		4Ø16	5.58	
RPC-10-1.5	Reactive Powder	4Ø10	2.18	1.5
RPC-12-1.5		4Ø12	3.14	
RPC-16-1.5		4Ø16	5.58	

*All specimens have closed ties of **Ø6@120.**

3.4. Support and Loading Condition

The column specimens were tested in a 300 ton capacity universal testing machine. Columns were placed vertically and eccentrically with respect to the vertical axis of the testing machine as shown in Figure 2.

Figure 2 Test set-up and instrumentation.

To apply a proper axial compression loading and transmit it to the column with accurate eccentricity, loading cap was manufactured having rectangular section (120×240 mm) and thickness of 20 mm, see Figure 3. The loading caps were made of high strength steel and each end of the columns was covered with loading cap. The lower end of the column was attached to the actuator of the machine, while the upper end was supported on the steel reaction cap of the machine. Both end supports were designed as hinged connections.

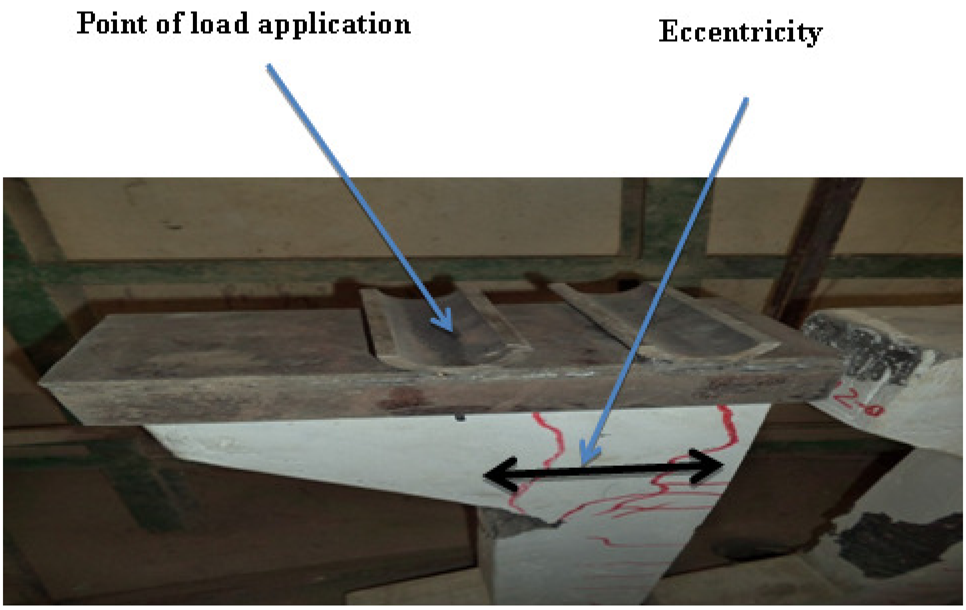

Figure 3 Loading cap

3.5. Measurements and Testing Procedure

During the test of each column, mid height lateral displacement has been measured by means of dial gauge placed at tension face of the tested column (Figure 2). Dial gauge readings were recorded for each load increment to obtain complete axial load-

midheight lateral displacement behaviour. The columns were tested under static loads, loaded gradually in successive increments of 5–10 kN, up to failure.

General behaviour of the tested column was monitored especially near failure where concrete crushing, spalling and/or buckling may take place. Also cracking developments of the column were observed during the test and crack patterns were mapped.

3.6. Strengthening Procedure

After failure, columns were prepared for strengthening. First, cracks were filled with a two component low viscosity epoxy resin using injection gun, and regions of crushed and/or spalled concrete were trowelled with epoxy modified cement mortar and left to cure. After a curing period of about 3 days, the column surfaces were smoothed (if rough or uneven) by grinding machine and cleaned by compressed air to obtain a sound, dry and contaminant free substrate.

A two part epoxy based resin (Sikadur – 330) was then brushed on to concrete surfaces within the middle portion between corbels, then, a CFRP sheet (SikaWrap – 230C, Figure 4) was carefully wrapped on the column (with 20 mm overlap) and rolled (without excessive force) parallel to the fiber direction until the resin was squeezed out between and through the fiber strands and distributed evenly over the entire sheet surface. After wrapping, the sheet was again coated with a layer of the epoxy resin to ensure that the sheet was fully soaked with resin. Figure 5 shows a strengthened column on the testing machine

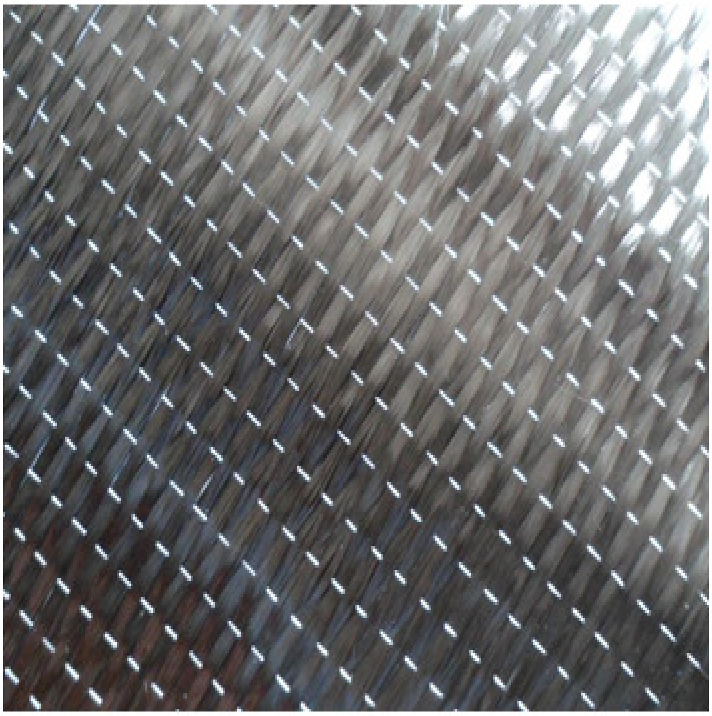

Figure 4 Sample of CFRP Sheet

3.7. Retesting after Strengthening

After completion of strengthening process, the columns were ready for retesting under the same loading conditions and testing procedure as original columns (see sections

3.4 and 3.5) except that cracking behaviour did not observed directly because concrete surfaces were covered by CFRP (Figure 5).

Figure 5 strengthened column under Retesting

4. RESULTS AND DISCUSSION

4.1. Original Columns

Experimental results of the tested columns in terms of effects of concrete type (compressive strength), main reinforcement and steel fibers on ultimate failure loads, general behaviour and axial load- lateral displacement behaviour, are presented and discussed in the following.

4.1.1. Ultimate Failure Loads

The experimentally obtained ultimate failure loads (P_u) of the tested columns are listed in Table 4.

Results showed that the use of non-fibrous RPC ($\mathbf{f_{cu}}$ = 89 MPa) increases ultimate load of eccentrically loaded columns by about 47% - 54% as compared to NC columns ($\mathbf{f_{cu}}$ = 39 MPa). Incorporating steel fibers in RPC columns with a volumetric ratio of 0.75% and 1.5% increases ultimate loads by about 22% - 38% and 82% - 86%, respectively (Figure 6).

It was also found that increasing main steel reinforcement from 2.18% to 3.14% and 5.58% increases ultimate loads by 11.4% and 23.5%, respectively for NC columns, 12.7% and 22.3% for non-fibrous RPC columns, 2.4% and 14.3% for RPC

columns with 0.75% steel fibers, and 11.9% and 26.4% for RPC columns with 1.5% steel fibers (Figure 7).

Table 4 Ultimate failure loads of tested columns

Column designation	f_{cu} (MPa)	V_f (%)	ρ (%)	P_u (kN)
NC-10-00	39	0	2.18	83
NC-12-00			3.14	92.5
NC-16-00			5.58	102.5
RPC-10-00	89	0	2.18	122
RPC-12-00			3.14	137.5
RPC-16-00			5.58	157.5
RPC-10-0.75	107	0.75	2.18	168
RPC-12-0.75			3.14	172
RPC-16-0.75			5.58	192
RPC-10-1.5	120	1.5	2.18	227
RPC-12-1.5			3.14	254
RPC-16-1.5			5.58	287

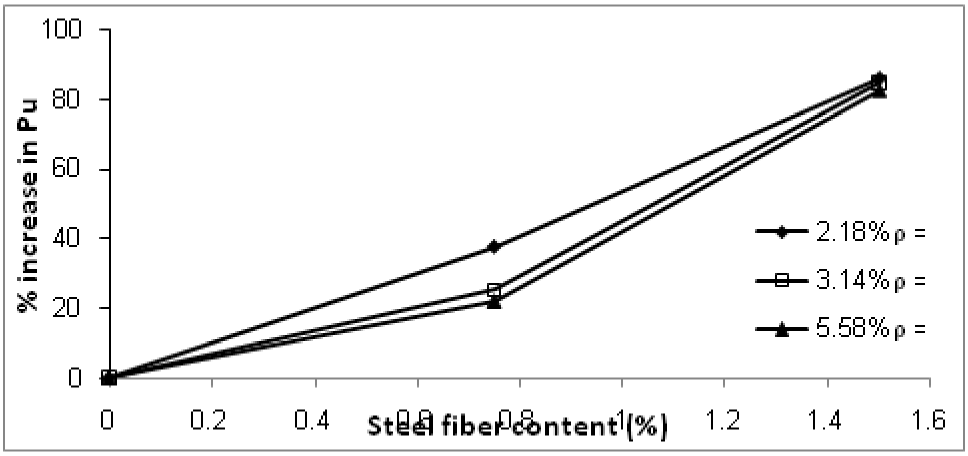

Figure 6 Variation of Ultimate Loads with Steel Fiber Ratio

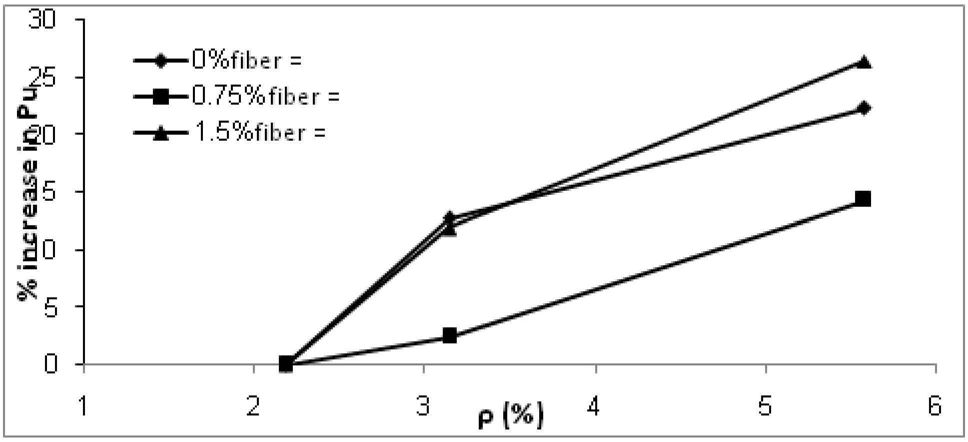

Figure 7 Variation of Ultimate Loads with Main Steel Ratio

The above results indicate that incorporating relatively high ratios of steel fibers (1.5% in particular) is more effective (regarding ultimate loads) than using higher ratio of main steel reinforcement (up to 5.58%) in eccentrically loaded RPC columns. Also, increasing compressive strength by using RPC instead of NC rises ultimate loads by higher rates than increasing main reinforcement (within the range used in this investigation). This agrees with the fact that compressive strength is the major factor affecting compression members. Steel fibers have increased ultimate loads by two ways: increasing compressive strength and bridging effect which arrests cracks widening thus delays failure.

4.1.2. Cracking Behavior and Failure Modes

Cracks patterns of the tested columns are shown in Figure 8. The general behaviour of the columns under test can be summarized as follows:

At early stages of loading, the column deformations were initially within the elastic range, then with load increasing, horizontal cracks were formed and propagated at and near midheight of the column tension face. As the load increases further, these cracks were extended toward the compression face crossing the neutral axis and other cracks appeared along the column height. At about 80% of ultimate failure load, the column began to buckle away of its axis. Buckling (which was more evident in lightly reinforced columns) continued and companied by cracks widening which followed by yielding of main reinforcement and then, failure.

For non-fibrous NC and RPC columns, concrete cover in compression face was suddenly exploded and/or spalled near failure, while the presence of steel fibers in RPC columns prevented or delayed cover spalling until the crushing strength of concrete is reached. Furthermore, fibrous RPC columns did not show any exploded spalling even at failure due to the arresting and confining effect of steel fibers which ensures more ductile behaviour.

Wider cracks (up to 5 mm) with greater spacing (about 100 mm) and less number were observed in NC columns than non-fibrous RPC columns (Figure 8a and b). Clear differences were observed in fibrous RPC columns (Figure 8c and d), where cracks were finer with close spacing and high numbers.

Finally, in addition to horizontal cracks, inclined cracks initiated at columns corners of tension face and propagated toward the compression face were observed near failure in highly reinforced columns (ρ = 5.58%) especially in non-fibrous

columns (NC-16-00 and RPC-16-00) as shown in Figure 8. This may be due to the stress concentration at these corners and absence of steel fibers.

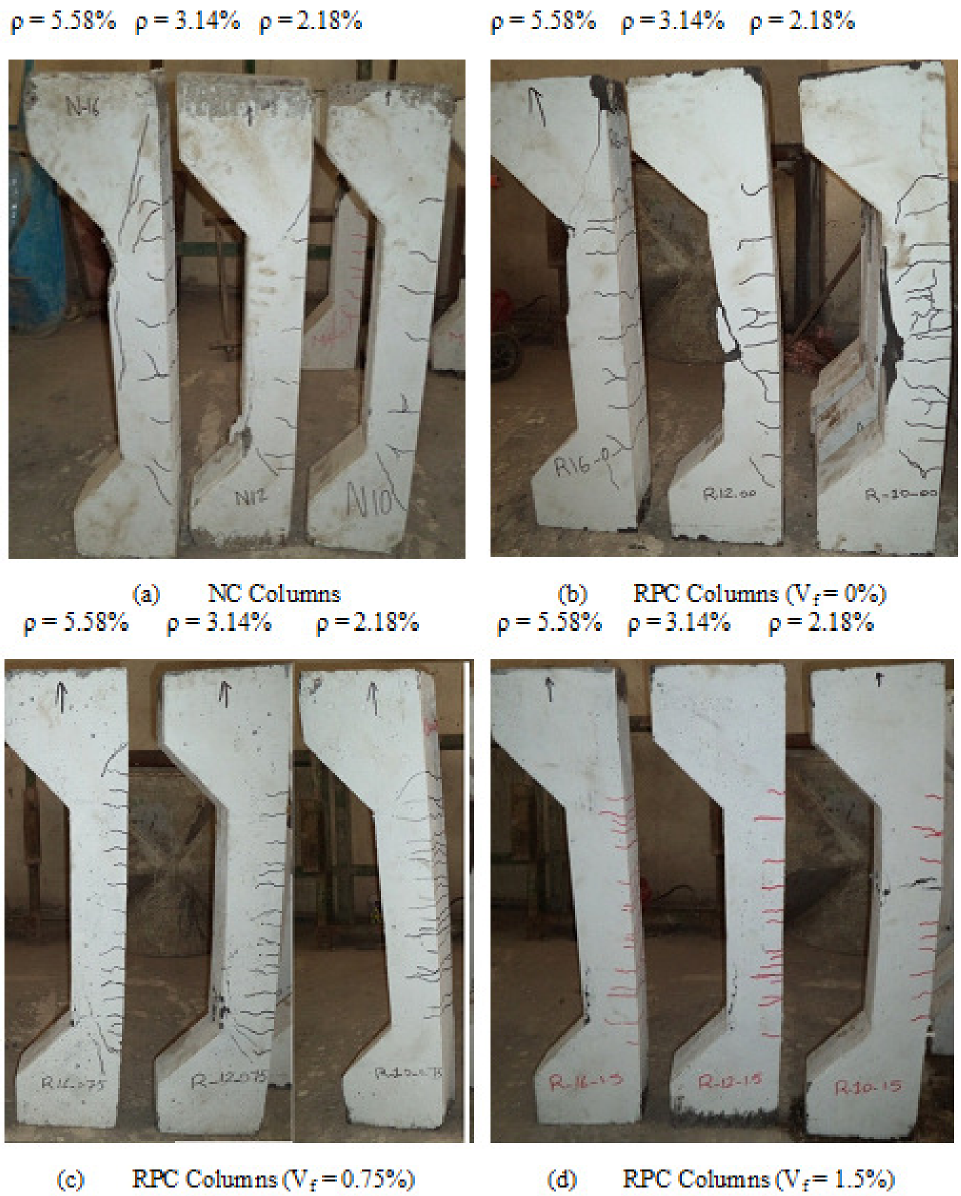

Figure 8 Original Columns after Testing

4.1.3. Load–displacement Behavior

Load–midheight displacement behaviour of all tested columns are illustrated in Figures 9 through 15.

In general, initial linear-elastic response was observed in the load-displacement curves. After this stage, a nonlinear ascending portion was observed which characterized by a loss of initial stiffness, mainly because the formation and propagation of horizontal cracks in the column tension face. Displacements continued increasing under increasing loads until failure which took place after the cracks were widened and the column buckled.

Figures 9 to 12 show that increasing main reinforcement ratio from 2.18% to 3.14% and 5.58% clearly reduced midheight displacement under certain load for NC and RPC columns. Positive effect of steel fibers are shown in Figures 13 to 15, where steel fibers obviously stiffened load–displacement curves as compared to curves of non-fibrous columns. Figures 13 to 15 also show that RPC columns have less displacement during the loading stages than NC columns, reinforced with same longitudinal steel ratio

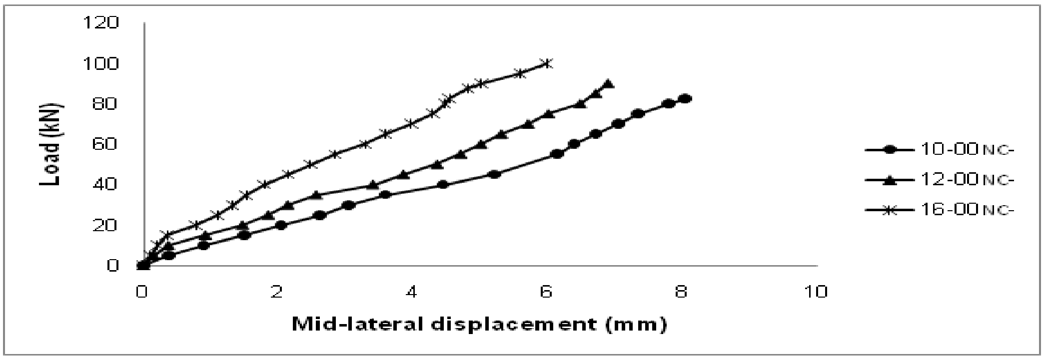

Figure 9 Load–Lateral Displacement Curves of NC Columns

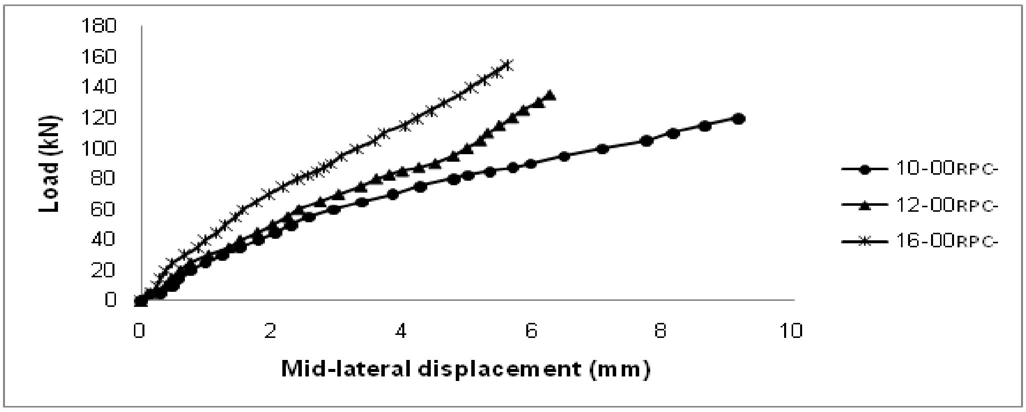

Figure 10 Load Lateral Displacement Curves of RPC Columns ($V_f = 0\%$).

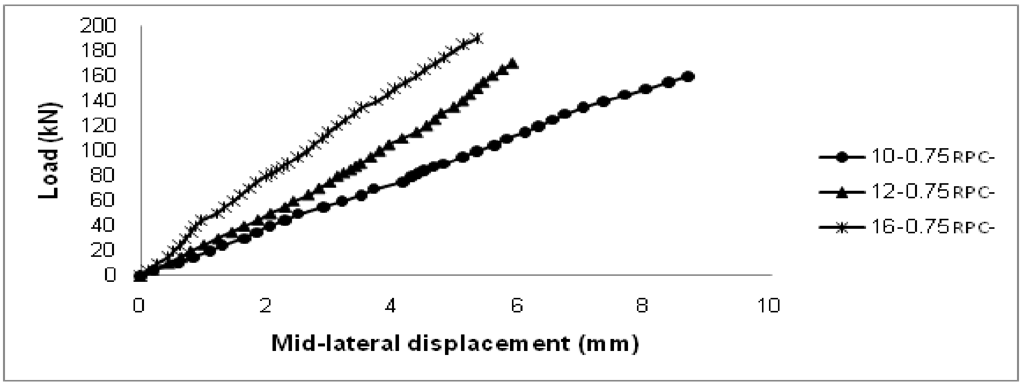

Figure 11 Load–Lateral Displacement Curves of RPC Columns ($V_f = 0.75\%$).

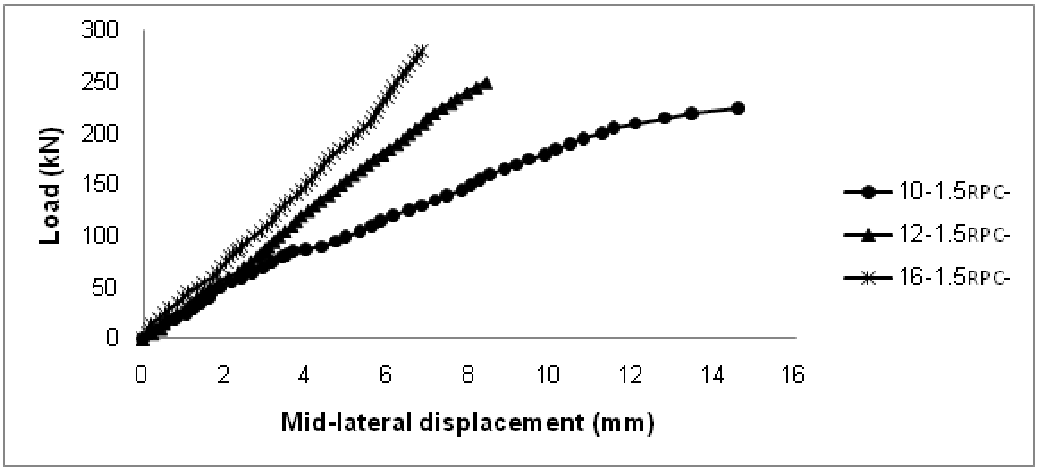

Figure 12 Load–Lateral Displacement Curves of RPC Columns (V_f = 1.5%).

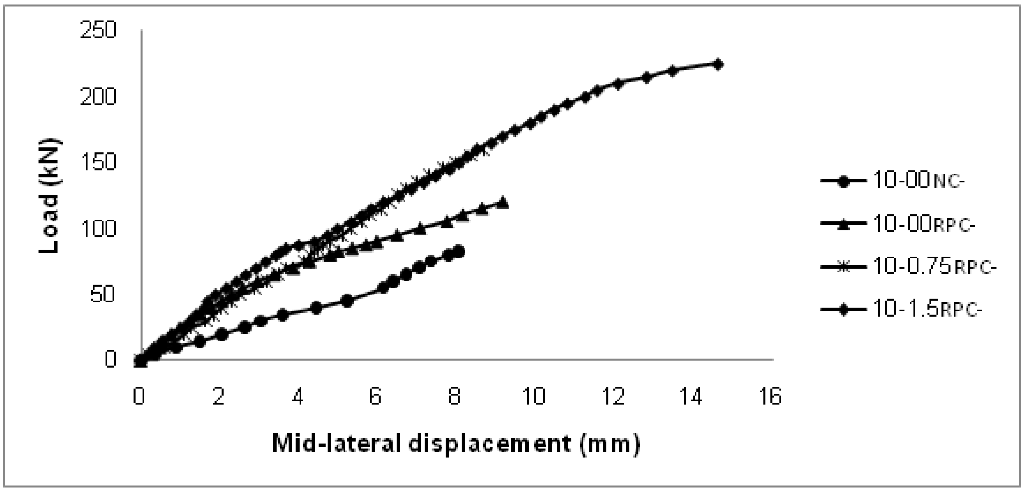

Figure 13 Load–Lateral Displacement Curves of RPC Columns (ρ = 2.18%).

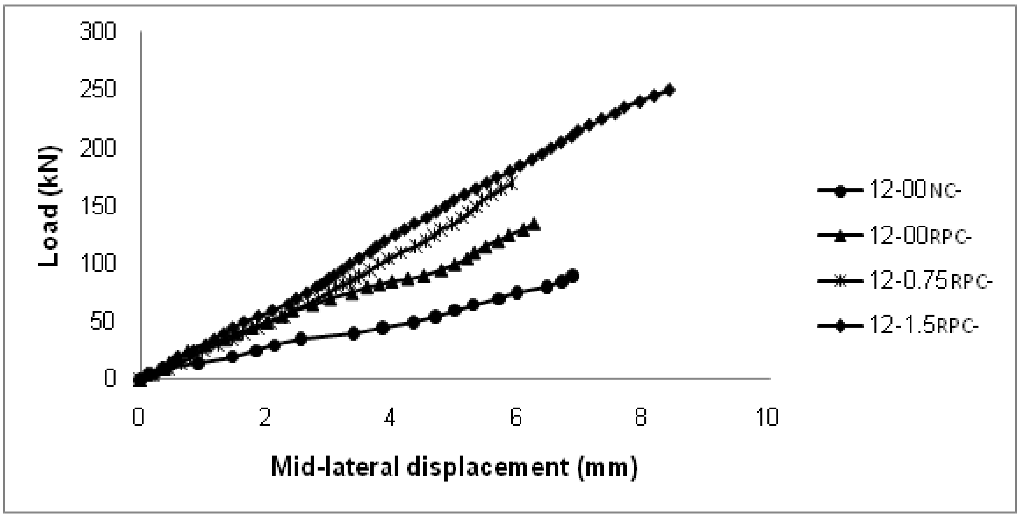

Figure 14 Load–Lateral Displacement Curves of RPC Columns (ρ = 3.14%).

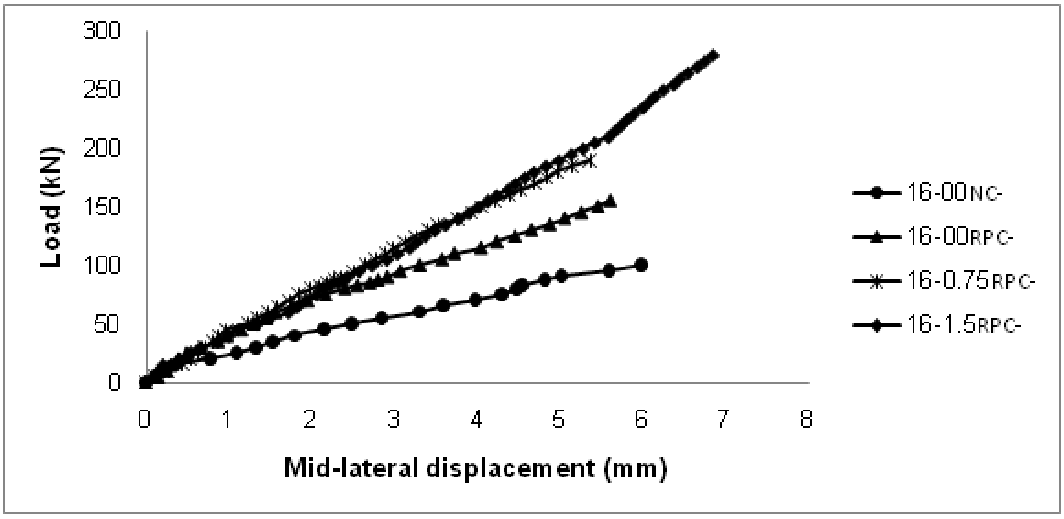

Figure 15 Load–Lateral Displacement Curves of RPC Columns (ρ = 5.58%).

4.2. Strengthened Columns

Behavior of columns strengthened by CFRP jacketing will now be discussed regarding their ultimate failure loads, failure modes and load–displacement characteristics as compared to the original columns.

Table 5 Ultimate failure loads of original and strengthened columns with their increasing ratios

Column designation	f_{cu} (MPa)	V_f (%)	ρ (%)	P_{uo}* (kN)	P_{us}** (kN)	Increasing ratio $(P_{us} - P_{uo})/P_{uo}$ (%)
NC-10-00	39	0	2.18	83	237	185.5
NC-12-00			3.14	92.5	252	172.4
NC-16-00			5.58	102.5	277	170.2
RPC-10-00	84	0	2.18	122	248	103.3
RPC-12-00			3.14	137.5	392	185.1
RPC-16-00			5.58	157.5	378	140.0
RPC-10-0.75	102	0.75	2.18	168	373	122.0
RPC-12-0.75			3.14	172	298	73.3
RPC-16-0.75			5.58	192	293	52.6
RPC-10-1.5	116	1.5	2.18	227	519	128.6
RPC-12-1.5			3.14	254	425	67.3
RPC-16-1.5			5.58	287	593	106.6

* P_{uo}= Ultimate load of original column, ** P_{us}= Ultimate load of strengthened column

4.2.1. Strengthening Effectiveness

The main purpose of strengthening any structural member regardless the method used, is to restore or increase its load carrying capacity. The method of CFRP jacketing used in this investigation to strengthen failed NC and RPC columns was proved

successful in terms of increasing ultimate loads (carrying capacity) of the tested columns up to 185% of those of original columns as listed in Table 5.

Table 5 shows that load increasing ratios were ranged from 52.6% (in RPC-16-0.75) to 185.5% (in NC-10-00). Higher ratios were recorded for NC columns (170% - 185%) and lower ratios in RPC columns with 1.5% steel fibers (52% - 122%). This again reflects the major role of steel fibers in taking the original columns to their full carrying capacities before failure. This also indicates the higher effectiveness of CFRP jacketing in strengthening non-fibrous lower strength columns especially those lightly reinforced (ρ = 2.18%). However, similar finding was reached by other researchers [11,15,16,18] as mentioned before.

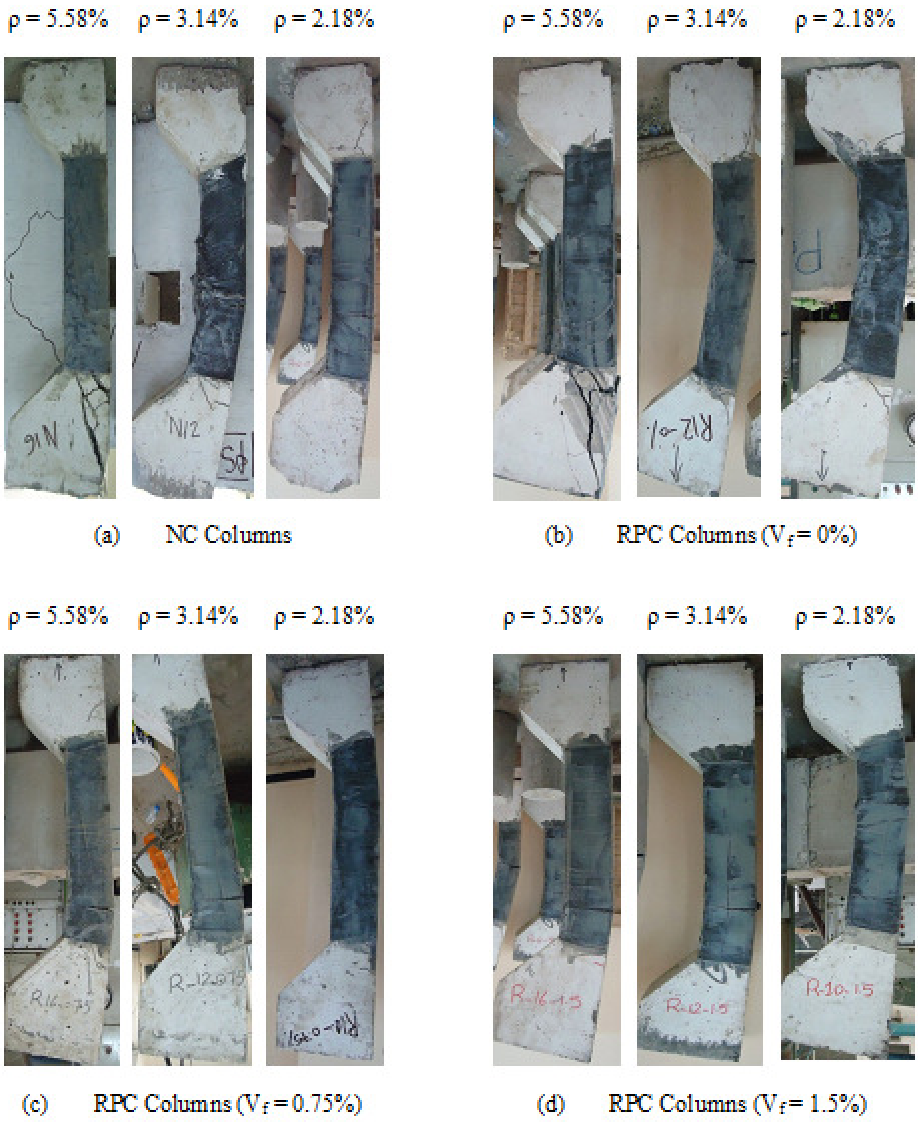

Figure 16 Strengthened Columns After Retesting

4.2.2. General Behavior of Strengthened Columns

Figure 16 shows the strengthened columns after retesting. The presence of CFRP jacketing in strengthened columns did not allow direct monitoring of the cracking behavior of these columns under test, but it can be expected that at first stage of loading, the response was somewhat similar to that of original columns. After that,

when new cracks were initiated or old cracks reopened, the tested column began to buckle under increasing load. Buckling was continued and the curvature of the column increased more and more until failure which generally characterized by formation of a wide crack (up to 10 mm or more) causing rupture in the CFRP sheet near midheight of column tension face (Figure 17).

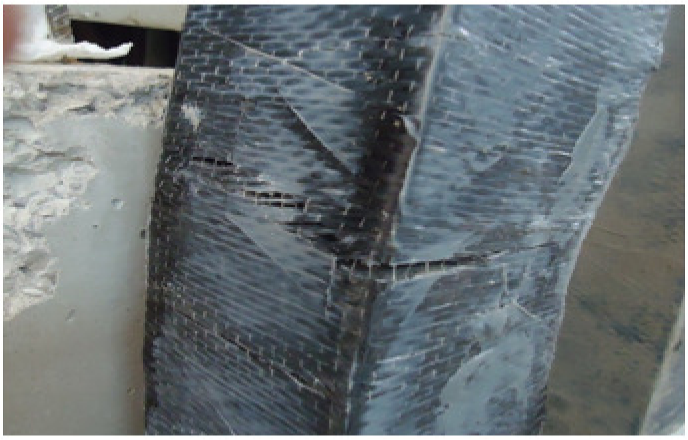

Figure 17 Rupture of CFRP Sheet at Failure

It is clearly shown that CFRP jacketing provides an effective confinement to the columns ensuring ductile failure with high deformation capacity (excessive curvature and wide cracks) allowing withstand greater loads. However, columns NC-16-00 and RPC-16-00 were failed by reopening of repaired cracks at columns heads as shown in Figure 16.

4.2.3. Load–displacement Behavior

Load–midheight displacement curves of both original and strengthened individual columns are illustrated in Figures 17 through 28.

It is clearly shown that CFRP strengthening highly stiffens the tested columns where steeper ascending parts (lower displacements) are observed. High ductility (in terms of area under load- displacement curve) was an important benefit obtained by using CFRP jacketing which allow ductile and gradual failure (flat failure portion in load-displacement curve); a desirable characteristic in structural elements, especially columns. Higher stiffness and ductility were indicated when high main steel ratios and/or high steel fibers ratios were used (Figures 18–29).

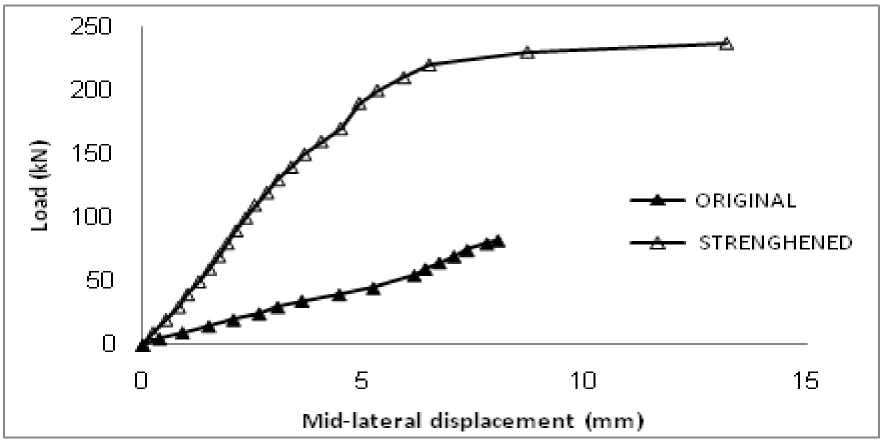

Figure 18 Load–Lateral Displacement Curves of Original and Strengthened Column NC-10-00

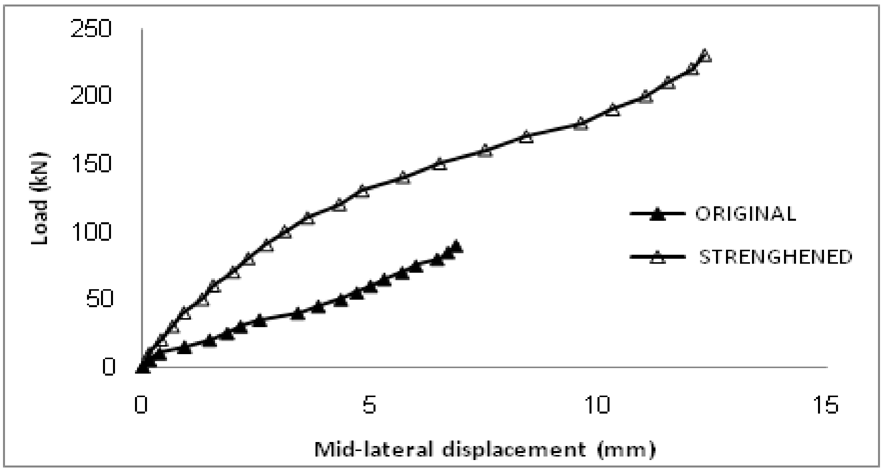

Figure 19 Load–Lateral Displacement Curves of Original and Strengthened Column NC-12-00

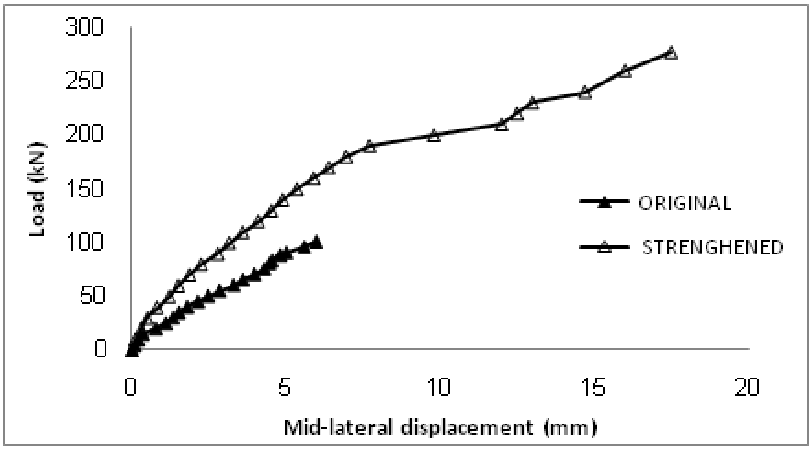

Figure 20 Load–Lateral Displacement Curves of Original and Strengthened Column NC-16-00

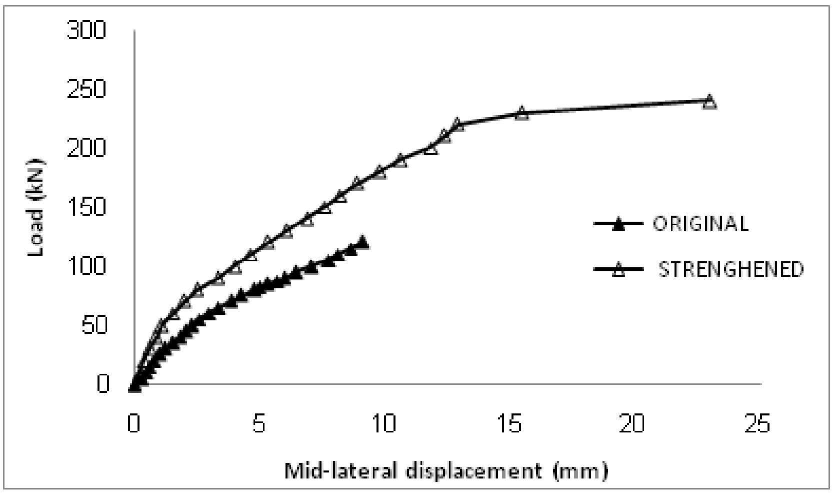

Figure 21 Load–Lateral Displacement Curves of Original and Strengthened Column RPC-10-00

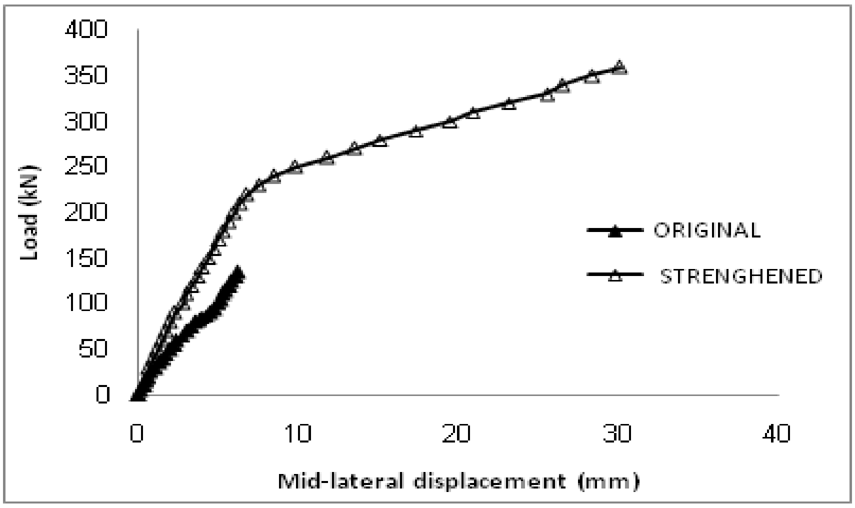

Figure 22 Load–Lateral Displacement Curves of Original and Strengthened Column RPC-12-00

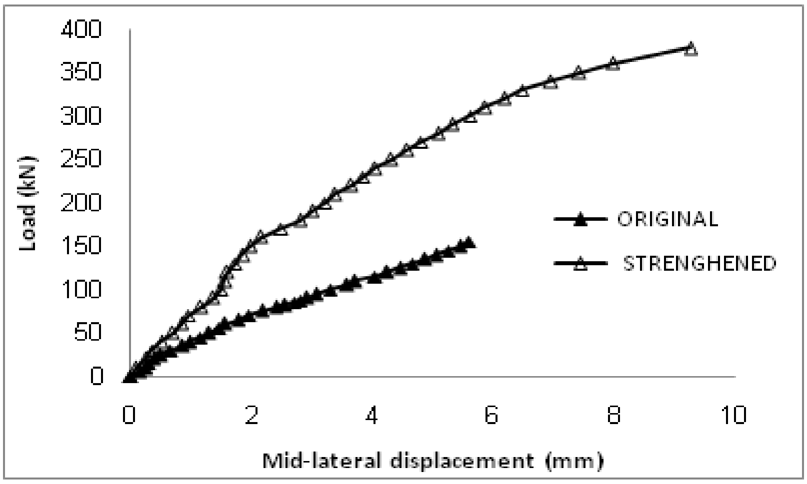

Figure 23 Load–Lateral Displacement Curves of Original and Strengthened Column RPC-16-00

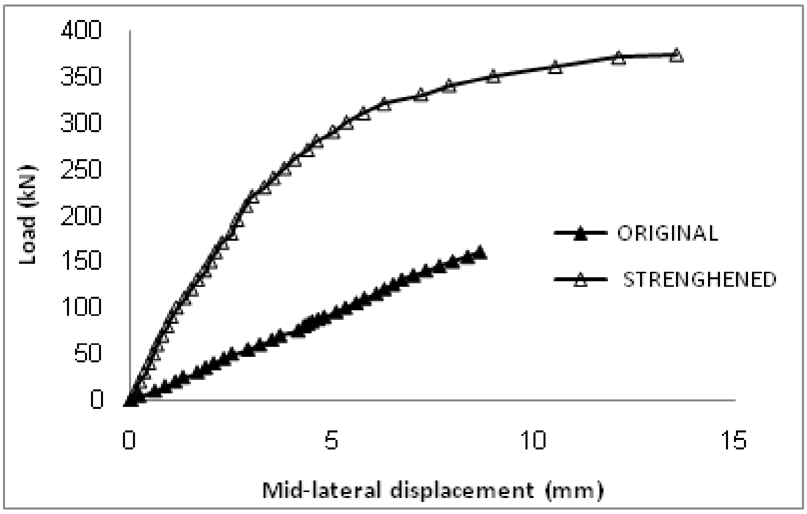

Figure 24 Load–Lateral Displacement Curves of Original and Strengthened Column RPC-10-0.75

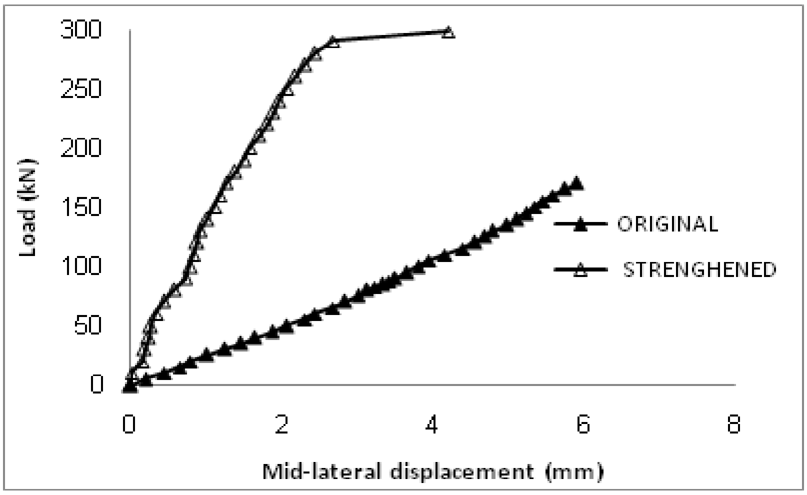

Figure 25 Load–Lateral Displacement Curves of Original and Strengthened Column RPC-12-0.75

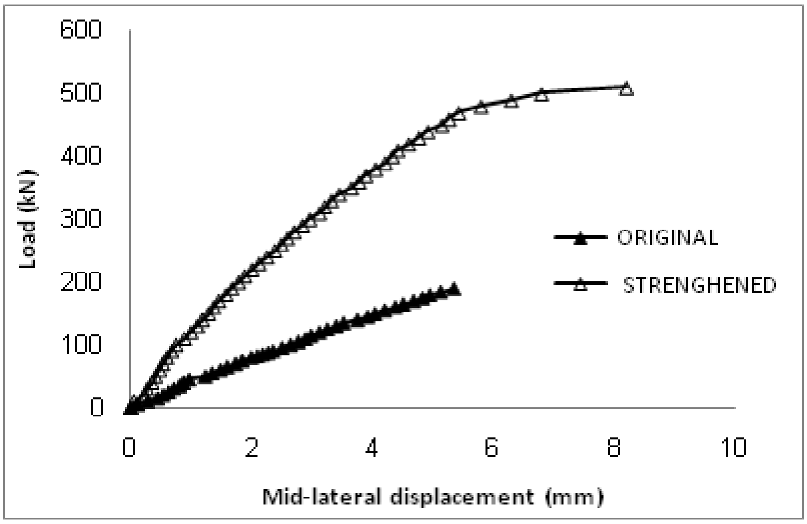

Figure 26 Load–Lateral Displacement Curves of Original and Strengthened Column RPC-16-0.75

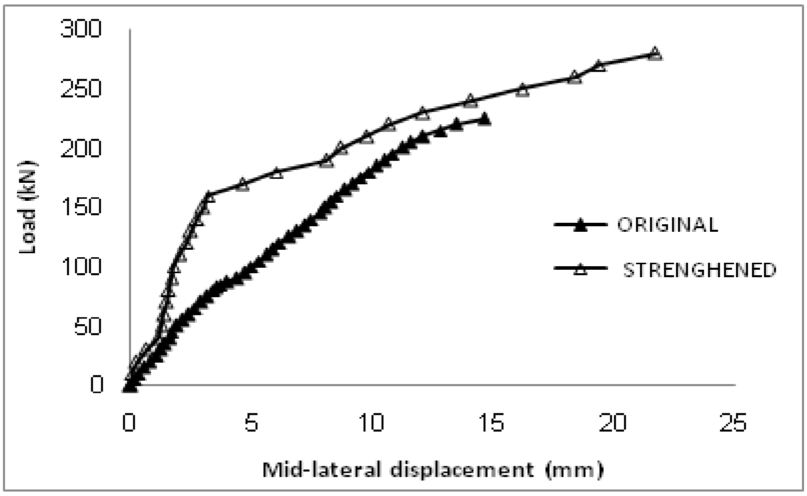

Figure 27 Load–Lateral Displacement Curves of Original and Strengthened Column RPC-10-1.5

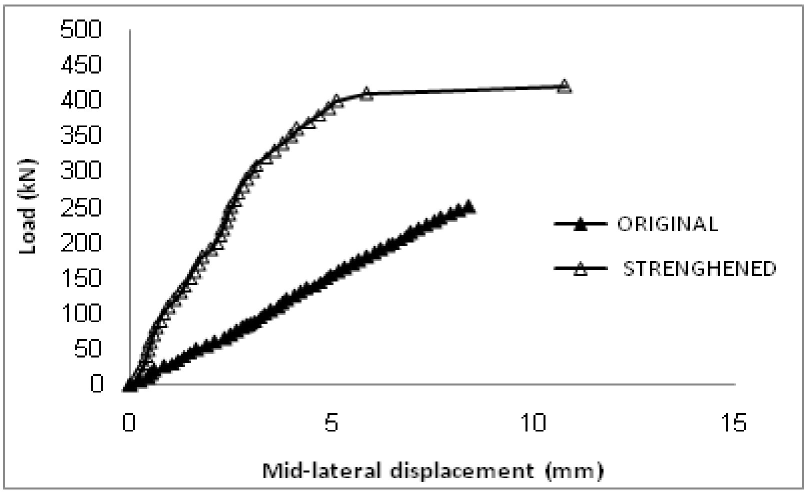

Figure 28 Load–Lateral Displacement Curves of Original and Strengthened Column RPC-12-1.5

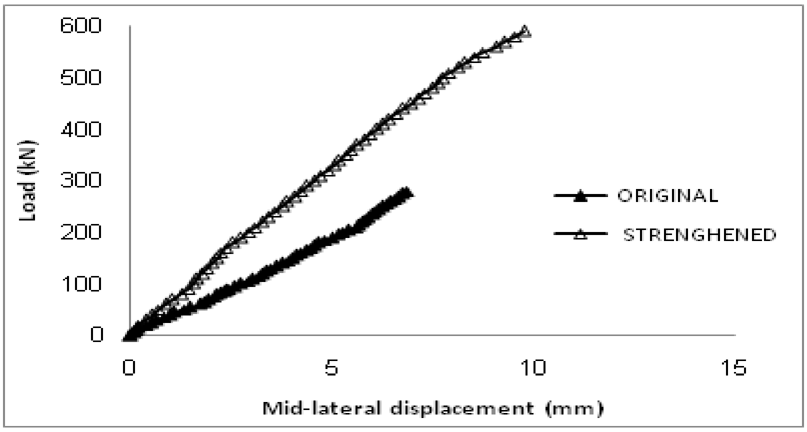

Figure 29 Load–Lateral Displacement Curves of Original and Strengthened Column RPC-16-1.5

5. CONCLUSIONS

1. Based on experimental results of the tests conducted on eccentrically loaded NC and RPC columns, the following main conclusions can be drawn:
2. Incorporating steel fibers in RPC columns substantially increases their ultimate failure loads up to 86% (at 1.5% steel fibers) and stiffens load-lateral displacement curves (reduces displacements).
3. Lower effects than described in (1) above were observed when main reinforcement ratio increases from 2.18% to 5.58% (about 27% maximum increase in ultimate load).
4. Presence of steel fibers in columns ensures ductile failure which characterized by closely distributed higher number of finer cracks in column tension face than non-fibrous columns without spalling of concrete cover in compression face.
5. Strengthening failed columns by CFRP jacketing increases their ultimate failure loads in the range of 52% to 185% of the original failure loads and highly stiffens load –lateral displacement curves.

6. CFRP jacketing was more effective in increasing ultimate loads of lower strength concrete columns than higher strength columns.
7. CFRP jacketing provides an effective confinement to the columns ensuring more ductile failure with higher deformation capacity (larger displacements and greater buckling curvature before failure) than original columns.

REFERENCES

[1] Richard, P. Reactive Powder Concrete: A New Ultra-High-Strength Cementations Material. 4th International Symposium on Utilization of High Strength/High Performance Concrete, Paris, France, 1996, pp. 1343–1349.

[2] Richard, P. and Cheyrezy, M. Reactive Powder Concretes with High Ductility and 200-800 MPa Compressive Strength. ACI SP144-24, American Concrete Institute, Michigan, USA, 1994, pp. 507–518.

[3] Richard, P. and Cheyrezy, M. Composition of Reactive Powder Concrete. *Cement and Concrete Research*, **25**(7), 1995, pp. 1501–1511.

[4] Sadrekarimi, A. Development of a Light Weight Reactive Powder Concrete. *Journal of Advanced Concrete Technology, Japan Concrete Institute*, **2**(3), October 2004, pp.409–417.

[5] Graybeal, B. FHWA Tech Note: Ultra High Performance Concrete, FHWA Publication No: FHWA-HRT-11-038, 2011, Federal Highway Administration, pp. 8.

[6] Malik, A. and Foster, S. Carbon Fiber-Reinforced Polymer Confined Reactive Powder Concrete Columns – Experimental Investigation. *ACI Structural Journal*, **107**(3), 2010, pp. 263–271.

[7] Setunge, S. et al. Review of Strengthening Techniques Using Externally Bonded Fiber Reinforced Polymer Composites. CRC Construction Innovation, Report 2002-005-C-01, pp. 59.

[8] Parvin, A. and Brighton, D. FRP Composites Strengthening of Concrete Columns under Various Loading Conditions. *Polymers*, **6**, 2014, pp. 1040–1056.

[9] Chowdhury, E. Behavior of Fibre Reinforced Polymer Confined Reinforced Concrete Columns under Fire Condition. PhD thesis, Queen’s University, Ontario, Canada, 2009, pp. 235.

[10] Olivova, K. and Blicik, J. Strengthening of Concrete Columns with CFRP. *Slovak Journal of Civil Engineering*, **1**, 2009, pp. 1–9.

[11] Benzaid, R. and Mesbah, H. Circular and Square Concrete Columns Externally Confined by CFRP Composite: Experimental Investigation and Effective Strength Models. Fiber Reinforced Polymers – The Technology Applied for Concrete Repair, Chapter 6, 2013, pp. 167–201.

[12] Amir, A., Naseer, A. and Azam, O. Strengthening of Existing Building Column Using FRP Wrap & GI Wire Mesh. *International Journal of Scientific & Engineering Research*, **4**(5), 2013, pp. 211–216.

[13] Rocca, S., Galati, N. and Nanni, A. Large-Size Reinforced Concrete Columns Strengthened with Carbon FRP: Experimental Evaluation. Third International Conference on FRP Composites in Civil Engineering, December 13–15, 2006, Florida, USA, pp. 4.

[14] Parvin, A. and Wang, W. Behavior of FRP Jacketed Concrete Columns under Eccentric Loading. *ASCE Journal of Composites for Construction*, **5**(3), August 2001, pp. 146–152.

[15] Li, J. and Hadi, M. Behaviour of externally confined high-strength concretecolumns under eccentric loading. *Composite Structures*, **62**, 2003, pp. 145–153.

[16] Hadi, M. Behaviour of FRP wrapped normal strength concrete columns under eccentric loading. *Composite Structures*, **72**, 2006, pp. 503–511.

[17] El Maaddawy, T. Strengthening of eccentrically loaded reinforced concrete columns with fiber-reinforced polymer wrapping system: Experimental investigation and analytical modeling. *ASCE Journal of Composites for Construction*, **13**, 2009, pp. 13–24.

[18] Song, X., Gu, X., Li, Y., Chen, T. and Zhang, W. Mechanical behavior of FRP-strengthened concrete columns subjected to concentric and eccentric compression loading. *ASCE Journal of Composites for Construction*, **17**, 2013,pp. 336–346.

[19] Al-Musawi, A. Experimental Study of Reinforced Concrete Columns Strengthened with CFRP under Eccentric Loading. M. Sc. Thesis, Al-Mustansiriya University, Baghdad, Iraq, 2012, pp. 120.

[20] Sadeghian, P., Rahai, A. and Ehsani, M. Experimental study of rectangular RC columns strengthened with CFRP composites under eccentric loading. *ASCE Journal of Composites for Construction*, **14**, 2010, pp. 443–450.